Submitted to the Astrophysical Journal Letters

Discovery of an ultra-cool subdwarf: LSR1425+7102, first star with spectral type sdM8.0

Sébastien Lépine[1,2,3], Michael M. Shara[1], and R. Michael Rich[4]

ABSTRACT

We report the discovery of the coolest subdwarf reported to date. The star LSR1425+7102 was discovered in our survey for faint high proper motion stars in the northern sky. Follow-up spectroscopy revealed the star to be a very red object with the characteristic signature of M subdwarfs: strong CaH bands but relatively weaker TiO bands. The CaH molecular band at $\approx \lambda 6900$Å is particularly strong. By extrapolating the empirical relationship between the strength of the CaH molecular band and the subdwarf subtype, we conclude that LSR1425+7102 is the first star to be discovered with spectral type sdM8.0.

Subject headings: Stars: late-type — stars: low-mass, brown dwarfs — — subdwarfs — stars: fundamental parameters — Galaxy: stellar content

1. Introduction

Metal-poor stars are rare in the neighborhood of the Sun, and the current sample of local subdwarfs is very limited. In particular, very few low-mass subdwarfs are known and, as a result, the bottom of the main sequence is very poorly constrained for metal poor stars. While we now have a well populated sequence of known low-mass, solar-metallicity red dwarfs extending well into the brown dwarf regime (Dahn *et al.* 2002; Hawley *et al.*

[1]Department of Astrophysics, Division of Physical Sciences, American Museum of Natural History, Central Park West at 79th Street, New York, NY 10024, USA, lepine@amnh.org, shara@amnh.org

[2]Kalbfleich research fellow

[3]Visiting Astronomer, KPNO

[4]Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles, CA 90095, USA, rmr@astro.ucla.edu

2002), we are still seriously lacking in nearby prototypes for bottom of the main sequence subdwarfs. The search for low-mass, low-luminosity subdwarfs is hampered not only by the fact that metal-poor stars are rare and low-mass subdwarfs are intrinsically faint, but also because late-type M subdwarfs do not show exceptionally red colors as ultra-cool M dwarfs do.

M subdwarfs, however, can be readily distinguished from M dwarfs because of their very characteristic spectral signature. The optical spectra of M dwarfs and subdwarfs are dominated by molecular absorption bands, mainly of oxides (TiO, VO) and hydrides (CaH, MgH, FeH). While the oxide bands dominate in M dwarf spectra, they are markedly weaker in subdwarfs, where the hydride bands dominate (Eggen & Greenstein 1965). The relative strengths of the TiO and CaH bands can thus be used as an objective, spectroscopic criterion in the identification and classification of M subdwarfs (Mould & McElroy 1978). A quantitative scheme for the spectroscopic classification of M dwarfs and subdwarfs was developed by Gizis (1997a, hereafter G97a) based on the strength of the CaH and TiO bands around 7000Å. Stars are objectively separated into three classes, the M dwarfs (M V), the M subdwarfs (sdM), and the extreme M subdwarfs (esdM), based on spectroscopic criteria. The metallicity range for each of the three classes corresponds roughly to [Fe/H]≈ 0.0 for M dwarfs, [Fe/H]$\approx -1.2 \pm 0.3$ for sdM, and [Fe/H]$\approx -2.0 \pm 0.5$ for esdM. Observations of M subdwarfs that are companions to F and G subdwarfs of known metallicities have confirmed the consistency of this scale (Gizis, & Reid 1997).

While there are now numerous examples of ultra-cool M dwarfs (Kirkpatrick, Henry, & Simons 1995; Kirkpatrick, Henry, & Irwin 1997), only a handful of subdwarfs with spectral subtype 6.0 or later are currently known. At the time the classification system of G97a was introduced, only one ultra-cool sdM was known: the high proper motion star LHS377 (spectral type sdM7.0). The coolest esdM then known was LHS1742a (esdM5.5). A follow-up spectroscopic survey of faint high proper motion stars from the LHS catalog (Luyten 1979) for which no spectra had been obtained yet, revealed the existence of two more very cool subdwarfs: LHS1035 (sdM6.0), and LHS1135 (sdM6.5) (Gizis, & Reid 1997). That survey also revealed LHS1826 to be the first extreme subdwarf with spectral type esdM6.0. Follow-up spectroscopy of new high proper motion stars in the southern sky by Schweitzer *et al.* (1999) lead to the discovery of the coolest esdM known to date, APMPM J0559–2903 (esdM7.0). Another ultra-cool sdM was found recently by Lépine, Rich, & Shara (2003) from a follow-up survey of newly discovered high proper motion stars in the northern sky: LSR2036+5059 (sdM7.5).

In this paper, we report the discovery of the fifth known subdwarf with spectral subtype 6.0 or later, and the coolest reported to date. This is the faint high proper motion star

LSR1425+7102, to which we assign a spectral type sdM8.0.

2. Proper Motion Discovery and Photometry

The high proper motion star LSR1425+7102 was discovered as part of our new search for high proper motion stars in the northern sky using the Digitized Sky Survey (Lépine, Shara, & Rich 2002), performed as a part of the NStars initiative. The star was found in a relatively low density field at a moderate galactic latitude (b=+44). The star is not recorded in the Luyten catalogs of high proper motion stars, and a search on Simbad (http://simbad.u-strasbg.fr/Simbad) around that location on the sky yielded no results, confirming that this high proper motion star is being reported here for the first time. The Digitized Sky Survey discovery fields are presented in Figure 1. The left panel shows the 1955 POSS-I red (103aE + red plexiglass) image of a $4.25' \times 4.25'$ field centered on the position of the star at epoch 2000.0. The right hand side shows the 1991 POSS-II red (IIIaF + RG 610) image of the same field. The motion of LSR1425+7102 over the 36 years period is very apparent. The star has a proper motion $\mu_{RA} = -0.61''\mathrm{yr}^{-1}$ and $\mu_{DEC} = -0.17''\mathrm{yr}^{-1}$. The coordinates of LSR1425+7102 are listed in Table 1 along with the various parameters mentioned in this paper.

We have found this star to match the star listed as 1610–0102604 in the USNO-1B catalog. The USNO-1B catalog gives the blue, red, and near infra-red photographic magnitudes from the POSS-II plates. This gives LSR1425+7102 photographic magnitudes b=20.8, r=18.6, and i=16.2, making it a fairly red object, consistent with an M dwarf or subdwarf. We also found LSR1425+7102 to match the source 2MASS 1425050+710209, which is listed in the *2MASS Point Source Catalog Second Incremental Release*. The 2MASS magnitudes yield an infrared color J–K=0.5, which is consistent with the star being a subdwarf. Observations show that all M dwarfs have J–K>0.7, and only M subdwarfs are found with J–K<0.7 (Leggett, Allard, & Hauschildt 1998).

3. Spectroscopy

The star LSR1425+7102 was observed on the night of 19 May 2002, at the 4-m Mayall telescope of the Kitt Peak National Observatory. A spectrum of the star was obtained with the R-C spectrograph equipped with the LB1A CCD camera, and mounted at the Cassegrain focus. We used the BL181 disperser (316 l/mm, blazed at 7500Å), with the OG530 order blocking filter. The star was imaged through a 1.5″ slit, yielding a 5Å spectral resolution.

Standard spectral reduction was performed with IRAF using the CCDPROC and SPECRED packages, including removal of telluric features. Calibration was derived from observations of the standard Feige 34 (Massey & Gronwall 1990). Both the target and the standard were observed at the smallest possible airmass (< 1.3) and with the slit at the parallactic angle to minimize slit loss due to atmospheric diffraction, providing excellent spectrophotometric calibration.

We measured the radial velocity of the star from the centroids of the K I $\lambda\lambda$7665,7699, Na II $\lambda\lambda$8183,8195, and Ca II $\lambda\lambda$8540,8660 atomic lines. After correction for the earth's motion in space, and accounting for uncertainties, we find an estimated heliocentric radial velocity $v_{hel} = -60 \pm 20$km s^{-1}.

4. Assignment of spectral type sdM8.0

A spectrum of LSR1425+7102 is plotted in Figure 2, where it is compared to the spectrum of LSR2000+3057, a known M6.0 V dwarf (Lépine, Rich, & Shara 2003), observed at a similar spectral resolution. The general slope of the spectral energy distribution in the 6000-9000Å range for both stars are very similar. Note also the great similarity in the Na I doublet profiles. The difference between the two stars clearly is in the relative strength of the CaH and TiO molecular bands. The TiO bands dominate in the M6.0V star, but they are much weaker in LSR1425+7102, in which the CaH bands are marginally stronger. It is remarkable that the TiO band at λ8430 is very weak in LSR1425+7102. The star thus clearly shows the classic signature of a subdwarf, although a very cool one.

We quantify the behavior of the CaH and TiO bands by calculating values for the CaH1, CaH2, CaH3, and TiO5 indices defined in Reid, Hawley, & Gizis (1995), and which serve as the main classification criteria for subdwarfs (see G97a). We find for LSR1425+7102 the following values: CaH1=0.309, CaH2=0.200, CaH3=0.306, and TiO5=0.307. To our knowledge, the very low value of the CaH3 index is the lowest ever measured in a low-mass star, a record previously held by the esdM7.0 star APMPM J0559–2903 (Schweitzer *et al.* 1999), for which CaH3=0.32 had been measured. This clearly makes LSR1425+7102 one the coolest subdwarfs to date.

The separation between the sdM and esdM classes as defined by G97a is based on the position of the star in the CaH2/TiO5 diagram. Under this system, LSR1425+7102 clearly falls in the range of sdM stars (see Figure 1 in G97a). The mean value of two separate relationships (respectively based on the CaH2 and CaH3 indices) are used to calculate the spectral subclass, rounded to the nearest half integer. For LSR1425+7102, it yields a spectral type sdM8.0. These spectral index to spectral subtype relationships were originally defined only to spectral subtype 7.0, but it seems reasonable to extrapolate them at least to spectral subtype 8.0, since the CaH band does not appear to begin to saturate yet.

In Figure 3, we plot CaH2+CaH3 against TiO5 for an extended sample of dwarfs, subdwarfs, and extreme subdwarfs. The points in the diagram represent all stars whose spectroscopic indices were published in G97a, Gizis, & Reid (1997), Cruz & Reid (2002), and Lépine, Shara, & Rich (2002), plus the esdM7.0 star APMPM J0559–2903 (Schweitzer *et al.* 1999), the esdM5.0 star LP 382-40 (Gizis, & Reid 1999) and LSR1425+7102 (this paper). All sdM and esdM with published values of CaH2, CaH3, and TiO5 are thus represented here. Many more nearby M dwarfs (>1600) have also had their spectral indices measured (Reid, Hawley, & Gizis 1995; Hawley, Gizis, & Reid 1996), but are not plotted on this graph. All the known ultra-cool sdM and esdM (spectral subtype 7.0 or later) are circled and labeled by name. The distribution has a significant gap in the vicinity of [CaH2+CaH3,TiO5]=[0.5,0.7], but the region occupied by the three known late-type sdM stars (including ours) suggest that the void may well be due to the small number of such stars actually discovered, rather than indicating a physical boundary in their spectroscopic properties.

5. Discussion and Conclusions

Because LSR1425+7102 is an sdM, its metallicity is $[Fe/H] \approx -1.2 \pm 0.3$. Based on the evolutionary models of Baraffe *et al.* (1997) for low-mass, metal-poor stars, a subdwarf with $[Fe/H] = -1.5$, J–K= 0.5 would have a mass $M \simeq 0.095 M_\odot$, while a subdwarf with $[Fe/H] = -1.0$, J–K= 0.5 would have a mass $M \simeq 0.088 M_\odot$. The magnitude and color relationships presented in Baraffe *et al.* (1997) are based on the "NextGen" model atmospheres, which does not include the formation of atmospheric dust. This model has since been superseded by the "DUSTY" atmosphere model Chabrier *et al.* (2000), which yields significantly different magnitudes and colors for low-mass stars with solar abundances. It is very possible that the use of the "DUSTY" model for metal-poor stars also yields slightly different results. Because of the uncertainty, we adopt for LSR1425+7102 a conservative mass estimate of $M = 0.09 \pm 0.01 M_\odot$.

We again use the models of Baraffe *et al.* (1997) to estimate the distance to LSR1425+7102. Their theoretical, absolute magnitudes for a metal-poor $0.09 M_\odot$ star with $[Fe/H] = -1.3$ are J=10.74, H=10.31, and K=10.27. This suggests a distance modulus $\simeq$4.1 for LSR1425+7102. Accounting for possible uncertainties in the models, we adopt a conservative distance estimate of 65±15pc. At that distance, the proper motion and radial velocity yield components of the space motion $U = -65 \pm 22$, $V = -177 \pm 35$, and $W = +64 \pm 27$, where U is in the direction of the galactic center, V is towards the direction of galactic rotation, and W towards the galactic north pole. These values make LSR1425+7102 a probable halo member.

Deep photometry of the globular cluster Messier 4 (Richer *et al.* 2002) has recently showed that the bottom of its main sequence extends to significantly fainter luminosities and cooler temperatures than suggested by the current sample of field sdM/esdM stars. Based of these results, Richer *et al.* (2002) have postulated the existence of very cool subdwarfs in the solar neighborhood, although they argued that these stars should be extremely rare (1 star in 30,000). Our discovery of LSR1425+7102 brings support to this hypothesis. The observation that at least one sdM8.0 star with halo kinematics does exist within 100pc of the Sun strongly indicates that similar objects must exist in large numbers throughout the Galaxy. Furthermore, the extended Messier 4 main sequence suggests that subdwarfs even cooler than LSR1425+7102 should also be found in the neighborhood of the Sun.

The current sample of spectroscopically identified cool and ultra-cool subdwarfs is thus still clearly lacking in representative objects. More efforts should be devoted to the search and spectroscopic identification of cool sdM and esdM stars, so that their contribution to the Galactic mass can be evaluated. A systematic spectral classification of faint stars with large proper motions should result in the recovery of more cool and ultra-cool subdwarfs. A more complete sample of sdM and esdM over a large range of temperatures and abundances would provide much needed constraints for current and future atmospheric models of low-mass, metal-poor stars.

This research program is being supported by NSF grant AST-0087313 at the American Museum of Natural History, as part of the NSTARS initiative.

REFERENCES

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1997, A&A, 327, 1054

Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. H. 2000, ApJ, 542, 464

Cruz, K. L., & Reid, I. N. 2002, AJ, 123, 2828

Dahn, C. C., Harris, H. C., Vrba, F. J., Guetter, H. H., Canzian, B., Henden, A. A., Levine, S. E., Luginbuhl, C. B., Monet, A. K. B., Monet, D. G., Pier, J. R., Stone, R. C., Walker, R. L., Burgasser, Adam J., Gizis, J. E., Kirkpatrick, J. D., Liebert, J., & Reid, I. N. 2002, AJ, 124, 1170

Eggen, O. J., & Greenstein, J. L. 1965, ApJ, 142, 925

Gizis, J. E. 1997, AJ, 113, 806 (G97)

Gizis, J. E., & Reid, I. N. 1997a, PASP, 109, 849

Gizis, J. E., & Reid, I. N. 1997b, PASP, 109, 1233

Gizis, J. E., & Reid, I. N. 1999, AJ, 117, 508

Hawley, S. L., *et al.* 2002, AJ, 123, 3409

Hawley, S. L., Gizis, J. E., & Reid, I. N. 1996, AJ, 112, 2799

Kirkpatrick, J. D., Henry, T. J., & Irwin, M. J. 1997, AJ, 113, 1421

Kirkpatrick, J. D., Henry, T. J., & Simons, D. A. 1995, AJ, 109, 797

Leggett, S. K., Allard, F., & Hauschildt, P. H. 1998, ApJ, 509, 836

Lépine, S., Rich, R. M., & Shara, M. M. 2002, AJ, in press

Lépine, S., Shara, M. M., & Rich, R. M. 2002, AJ, 124, 1190

Luyten W. J. 1979, LHS Catalogue: a catalogue of stars with proper motions exceeding 0.5" annually, University of Minnesota, Minneapolis (*CDS-ViZier catalog number I/87B*)

Massey, P., & Gronwall, C. 1990, ApJ, 358, 344

Mould, J. R., & McElroy, D. B. 1978, ApJ, 220, 935

Reid, I. N., Hawley, S. L., & Gizis, J. E. 1995, AJ, 110, 1838

Richer, H. B., Brewer, J., Fahlman, G. G., Gibson, B. K., Hansen, B. M., Ibata, R., Kalirai, J. S., Limongi, M., Rich, R. M., Saviane, I., Shara, M. M., & Stetson, P. B. 2002, ApJ, 574, L151

Schweitzer, A., Scholz, R.-D., Stauffer, J., Irwin, M., & McCaughrean, M. J. 1999, A&A, 350, L62

AAS LaTeX macros v5.0.

Table 1. Basic Data for LSR1425+7102

Datum	Value	Units
RA (2000.0)	14:25:04.81	h:m:s
DEC (2000.0)	+71:02:10.4	d:m:s
μ	0.635	$''$ yr^{-1}
pma	74.7	$^\circ$
v$_{hel}$	-65±20	km s^{-1}
b	20.8±0.5[1]	mag
r	18.6±0.5[1]	mag
i	16.2±0.5[1]	mag
J	14.83±0.04[2]	mag
H	14.43±0.06[2]	mag
K$_s$	14.34±0.10[2]	mag
CaH1	0.309[3]	
CaH2	0.200[3]	
CaH3	0.306[3]	
TiO5	0.307[3]	
Spectral Type	sdM8.0	
Distance	65±15	pc
U	-65±22	km s^{-1}
V	-177±35	km s^{-1}
W	64±27	km s^{-1}

[1]Photographic B, R, and I magnitudes from USNO B-1.0 catalog.

[2]Infrared magnitudes from the 2MASS survey.

[3]Spectroscopic indices (see text).

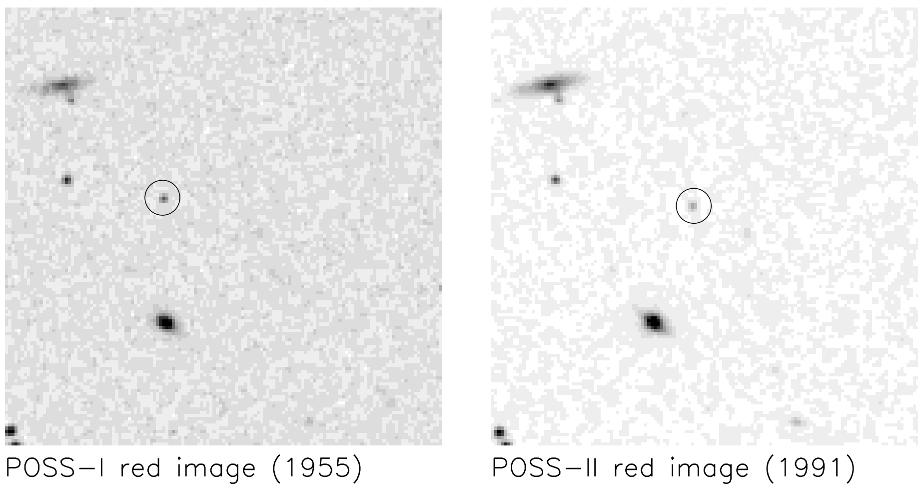

Fig. 1.— The new high proper motion star LSR1425+7102. Left: red plate of the first epoch Palomar Sky Survey, obtained in 1955. Right: red plate of the second epoch Palomar Sky Survey, obtained in 1991. All the fields are $4.0'$ on the side, with north up and east left. Circles are drawn centered on the location of LSR1826+3014 at each epoch. The star is moving with a proper motion $\mu = 0.635'' \mathrm{yr}^{-1}$.

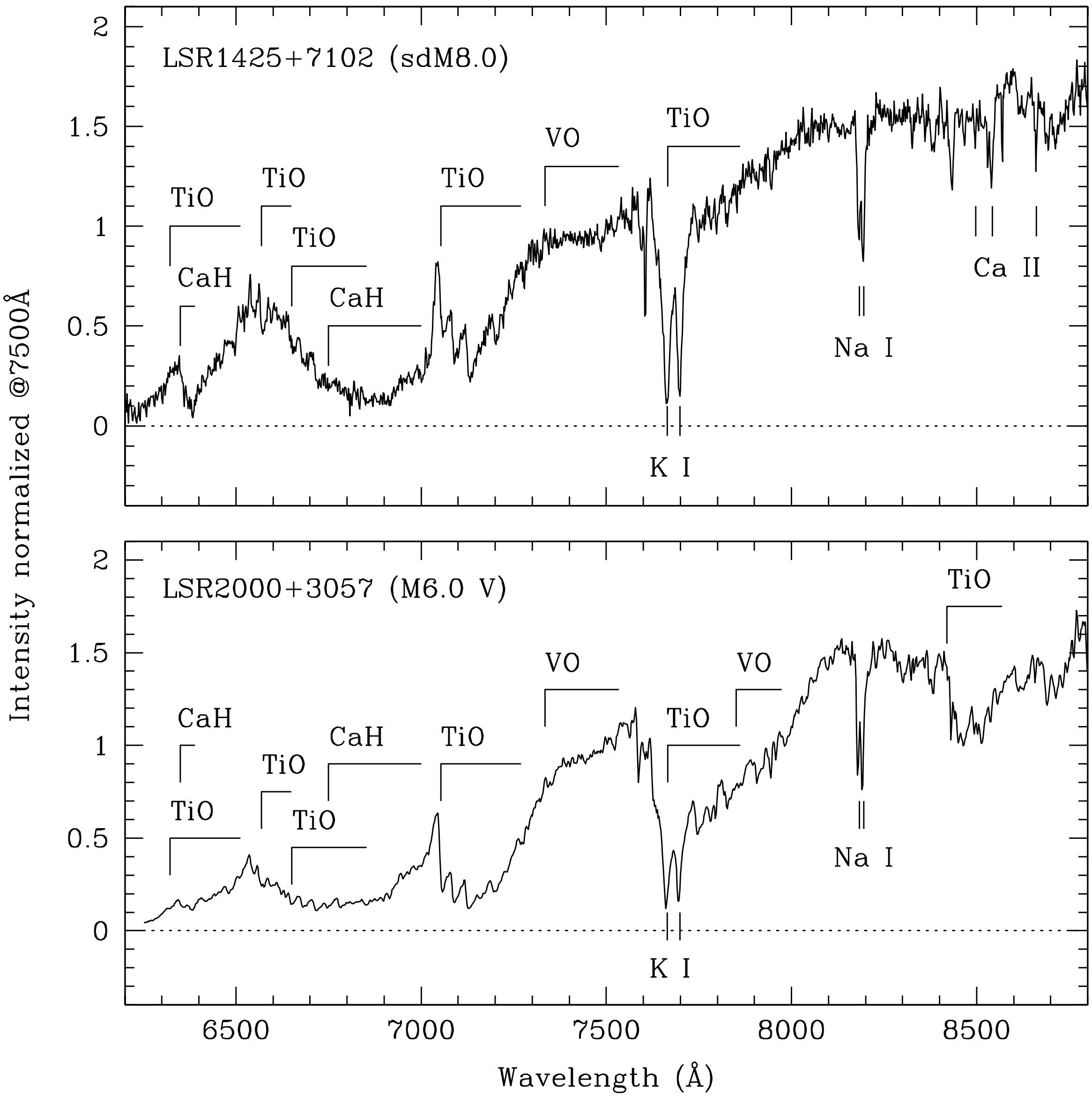

Fig. 2.— Optical spectrum of the sdM8.0 high proper motion star LSR1425+7102 obtained with the R-C spectrograph on the 4m Mayall Telescope at KPNO (top). Shown for comparison is a spectrum of the M6.0 V star LSR2000+3057 (bottom). The very deep CaH band and the very red spectral energy distribution point to a very late spectral type for LSR425+7102, but the TiO bands are conspicuously weak as compared with those of the M6.0 V star. Thus LSR1425+7102 is more consistent with a low metallicity M subdwarf. The depth of the CaH bands suggests a spectral type sdM8.0, making LSR1425+7102 the coolest subdwarf known, and the first of its subtype.

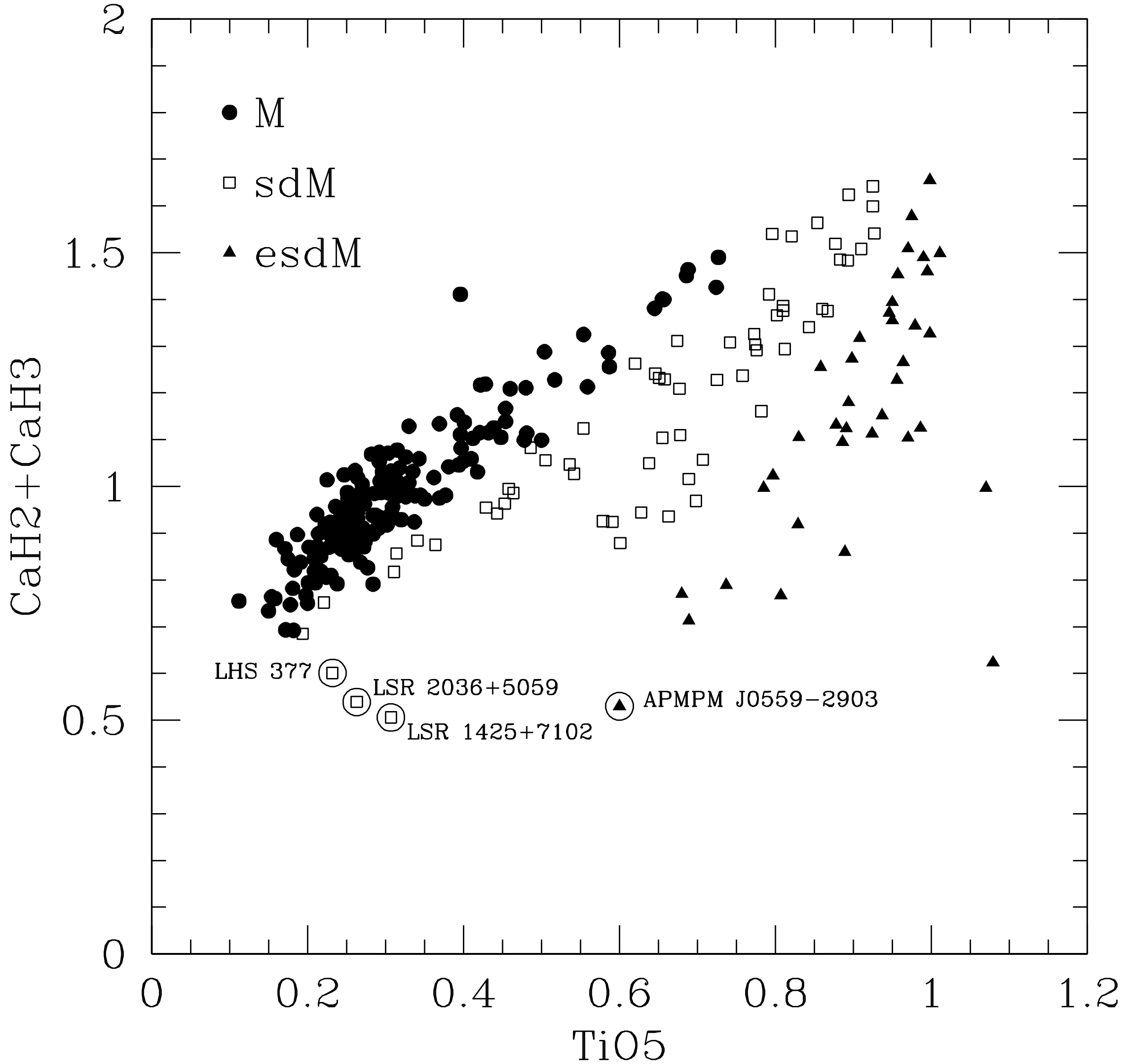

Fig. 3.— Distribution of M dwarfs, subdwarfs (sdM), and extreme subdwarfs (esdM) in the CaH2+CaH3 versus TiO5 spectral indices diagram (see text). Early-type stars are on the upper right of the distribution, late-type stars on the lower left, and the different metallicity classes are well segregated. This distribution is complete for sdM and esdM with published values of CaH2, CaH3, and TiO5. Ultra cool sdM and esdM (subtype 7.0 and later) are circled and identified by name.